

# Optimization of the Multi-turn Injection Efficiency for Medical Synchrotron

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## Abstract

We present a method for optimization of the multi-turn injection efficiency for medical synchrotron. We show that for given injection energy the injection efficiency can be greatly enhanced by choosing transverse tunes appropriately as well as optimizing the injection bump and the number of turns required for beam injection. We verify our study by applying the method to the Korea Heavy Ion Medical Accelerator (KHIMA) synchrotron which is currently built at the campus of Dongnam Institute of Radiological and Medical Sciences (DIRAMS) in Busan, Korea. First the frequency map analysis is performed with the help of ELEGANT and ACCSIM codes. The tunes which yield the good injection efficiency are then selected. With these tunes the injection bump and the number of turns required for injection are then optimized by tracking a number of particles up to one thousand turns after injection beyond which there is no further beam loss. Results for optimization of the injection efficiency for proton ion are presented.

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## I. INTRODUCTION

One of the promising methods for treatment of malignant tumors is the particle beam therapy. Specifically, there are numerous positive reports on effectiveness and prognosis of ion beam therapy as a non surgical treatment [1] using proton or heavier ion such as a carbon ion, and as a result the ion beam therapy is increasingly popular worldwide.

After Bragg peak property of an ion beam was found to be better than the conventional photon beam in curing patients with tumor, first clinical experience on a human being with a proton beam was reported by researchers in University of California, Berkeley in 1954 [2]. Soon after that many proton facilities were developed around the world. In 1990, the world first hospital-based proton therapy facility was constructed in Loma Linda, USA [2]. So far there are about forty operating proton facilities worldwide and the total number of patients treated by particle beam therapy exceeded 100,000 [2]. Success of these facilities stimulated the construct of more ion beam facilities.

In 1996, design study of a proton-ion beam accelerator for tumor treatment began to explore the possibility of building such a facility in Europe [3]. The aim of this study, called Proton-Ion Medical Machine Study (PIMMS), is to design a compact medical accelerator for acceleration of a proton beam and a carbon beam. The result was reported in 1999 [3].

Of particular importance of this design is a systematic study of beam injection into and extraction from a synchrotron. An issue associated with the injection of an ion beam is the space-charge effect which is especially pronounced at low energy of a beam. It is a repulsive force due to Coulomb interaction of charged particles that is inversely proportional to  $\gamma^2$  where  $\gamma$  is the usual relativistic factor. This means that high energy of injected beam is preferred, but high injection energy means high cost of the injector accelerator, usually linear accelerator. Therefore, an optimization study of the injection energy is necessary. Such study has been performed extensively during PIMMS [3]; the injection energy in PIMMS is 7 MeV/u.

Another important aspect related with the beam injection into a synchrotron is to maximize the injection efficiency. In any event maximization of the injection efficiency has to be achieved in particle accelerators. However, in a medical synchrotron employing multi-turn injection this is particularly important because the beam is accumulated turn by turn until desired beam current is reached. In the multi-turn injection scheme, injection is achieved

with the help of time-varying bump magnets. The phase space occupied by injected beams in the injection plane (usually horizontal plane) is diluted after injection (see for example Figs. 3, 6, 7, 8) and therefore the effective beam emittance in the injection plane is very large, usually around  $100 \pi \text{ mm mrad}$ . Although the acceptance of a synchrotron is designed in such a way that it is greater than the effective beam emittance, beam loss can occur immediately after injection or during acceleration due to various reason. Injection and extraction septa cause the main limitation in defining the acceptance of synchrotron. It is of utmost importance to design an injection scheme carefully to minimize the beam loss.

The purpose of the present paper is to investigate a way to enhance the beam injection efficiency in a synchrotron employing the multi-turn injection. Especially we focus on searching optimal transverse tunes at injection which maximize the injection efficiency. Assuming linear rise and fall of the bump magnets' pulse, effect of the pulse duration and bump angle on the injection is also examined. To verify our study we take the synchrotron lattice from Korea Heavy Ion Medical Accelerator (KHIMA) currently built in Busan, which is the first medical accelerator for heavy ion therapy in Korea. In many aspects, KHIMA follows the PIMMS design. It has a capability of accelerating proton ion or carbon ion; different injection linacs for each ion. More details of the KHIMA synchrotron is described elsewhere [4].

This paper focuses on the proton injection instead of carbon ion. It is mainly because for the same injection energy per nucleon the space-charge effect is more pronounced for proton than carbon ions such as  $^{12}\text{C}^{6+}$ .

This paper is organized as follows: In Section 2, the multi-turn injection scheme in KHIMA synchrotron is introduced. Section 3 presents the tune survey so that dependence of transverse tunes on the injection efficiency is shown. Section 4 describes the effect of bump magnet's angle and the pulse duration. Finally, Conclusion is given.

## II. MULTI-TURN INJECTION

The KHIMA synchrotron's circumference is 75 m and it has two straight sections with zero dispersion. An electrostatic injection septum (EIS) and a magnetic extraction septum are located respectively in these two straight sections. Table I shows baseline parameters for injection.

TABLE I: Parameters for Injection

Parameters	Value
Nominal energy	7 MeV/u
$\eta_x/\eta_y$ at the injection point	0 / 0
$\eta'_x/\eta'_y$ at the injection point	0 / 0
Horizontal and vertical position of the injection point	48.5 mm / 4.5 mm
Horizontal rms emittance	1 $\pi$ mm mrad
Vertical rms emittance	1 $\pi$ mm mrad

so that they have same values with the values of synchrotron at the injection point. The multi-turn injection scheme makes it possible to stack the horizontal machine acceptance with successive injection of beams from the injector linac [5]. Applying Liouville's theorem when a number of beams are injected by turn by turn, injected beams in later turn should be injected to local phase-space region which is not filled with injected beams in earlier turn. This is feasible when each beam that is injected in different order follows different closed orbit path because the injection point is fixed. The closed orbit path is controlled with the help of bump magnets which are capable of moving the closed orbit path away from the design orbit (Fig. 1) Setting bump magnets with linearly decreasing kick angle is one of proper ways to stack each injected beam in order. The beam injected in the first turn goes through the most long, distorted orbit and rotates by  $2\pi\nu_x$  radian in the phase space until the second beam is injected. At the same time, the closed orbit and the first beam are moving toward the design orbit as the second beam comes in. After repeated turns for injection, the machine acceptance is occupied densely and the closed orbit follows the design orbit. In other words, when the multi-turn injection is finished, composition of the machine acceptance is that a beam injected earlier occupies inner region and a beam injected later occupies outer region in sequence.

Many parameters affect how the injection scheme works ; betatron tunes, initial kick angle of bump magnets, number of turns for injection, angle of injected beam, twiss parameters of injected beam, and so on. Finding the best combination of those parameters is difficult

because it is a multi-dimensional optimization problem.

In this study, we mainly focus on the effect of betatron tunes and parameters associated with the bumped orbit such as kick angle and pulse duration of bump magnets. In this paper, the injection efficiency is defined as the percentage of number of survived particles divided by number of injected particles.

$$\text{Injection efficiency} = \frac{N_{\text{survived}}}{N_{\text{injected}}} \times 100(\%) \quad (1)$$

In this investigation 1000 macro particles are injected per each turn with rms horizontal and vertical beam emittances of  $1 \pi$  mm mrad and the total number of turns for injection is set to be 20 for tune survey. Then the number of turns for injection (i.e. bump-pulse duration) is varied to examine its effect on the injection efficiency. Number of survived particles is counted after the 20-turn injection and then additional 1000 turns are tracked to count still remaining particles before acceleration. ELEGANT code [6] was utilized for tune matching and ACCSIM code [7] was then used for particle tracking during and after injection.

### III. TUNE SURVEY

For later comparison the initial tunes are chosen to be ( $\nu_x = 1.73$  and  $\nu_y = 1.47$ ) and various beam dynamics studies have been performed with these tunes [4]. Also, the initial kick angle of the bump magnets is 4.8 mrad and the kick angle collapses to zero in 20 turns. With these parameters, the injection efficiency was calculated to be 33.5 % which is the baseline efficiency to be compared with.

Search for optimal horizontal and vertical tunes is carried out by varying tunes in steps of 0.01 from  $\nu_x$ ,  $\nu_y = 1$  to 2. Per each tune, zero dispersion in the straight sections is maintained while chromaticities are kept constant. Also Twiss parameters at the injection point are maintained for each tune.

Space-charge effect is not included during the computation because if the space-charge is included the computing time increases significantly. However, the effect of the space charge on the injection efficiency was examined once the optimal tunes were selected as shown in the below.

Figure 2 shows the footprint for injection efficiencies plotted on the tune diagram with

resonance lines up to third-order. Poor injection efficiencies around the third-order resonance line  $\nu_x + 2\nu_y = 3$  can be seen. From this figure, we have selected (1.82, 1.30) for horizontal and vertical tunes. At these tunes, the injection efficiency is increased to 41.5 % and therefore the new tunes yield eight percentage-point increase in the injection efficiency.

Figure 3 shows normalized horizontal phase-space portraits ( $p_x = \beta_x x' + \alpha_x x$  where  $\alpha_x$  and  $\beta_x$  are the usual twiss parameters) (a) for initial tunes (1.73, 1.47) and (b) for new tunes (1.82, 1.30). Comparing these plots it is seen clearly that injected particles with higher injection efficiency occupy denser and smaller phase-space area, thus verifying the superiority of the new tunes. Note that not all particles are survived after injection as Fig. 3 indicates the total number of pulses is less than 20.

#### IV. OPTIMIZATION OF THE BUMP MAGNET PARAMETERS

To explore possibility of enhancing the injection efficiency further, dependence of the initial kick angle and the pulse duration of the bump magnets on the injection efficiency were investigated with the new tunes. In KHIMA synchrotron there are two injection bump magnets and one electrostatic injection septum, in addition to one electrostatic extraction septum. The phase advance between the bump magnets is approximately  $\pi$  radian, so the bump is closed. Horizontal aperture limit of the EIS is 41 mm. However, the limitation of the aperture in the KHIMA synchrotron is set by electrostatic extraction septum (EES), which is 35 mm; most of the particle loss occurs at the position of this septum.

If there is only one septum whose horizontal aperture limits the acceptance of an accelerator, it is desirable for linear bump (i.e. rise and fall of the bump pulse are linear) for injection to satisfy the following condition:

$$\delta_{\text{bump}} = \nu_{\text{frac}}(2a + d_{\text{sep}}), \quad (2)$$

where  $\delta_{\text{bump}}$  is the orbit shift per one revolution,  $\nu_{\text{frac}}$  for fractional tune in the injection plane,  $a$  the radius of the injected beam at the position of the septum, and  $d_{\text{sep}}$  is the effective septum thickness [8]. This equation implies that the pulse duration (or slope of the pulse collapse) of the linearly falling bump magnet affects the injection efficiency. Also the maximum kick angle of the bump magnet should be made such that the bumped orbit is close to the injected beam to minimize the betatron oscillation amplitude of the injected

beam.

In our study, we have searched the optimal initial kick angle of the bump magnets and number of turns needed for the bump to decrease to zero. The result is shown in Fig. 4 where the footprint for injection efficiencies as functions of initial bump angle and the bump duration. The new betatron tunes were assumed, i.e. (1.82, 1.30). Figure 4 indicates that there is a large island region showing higher injection efficiency. We have chosen 4.2 mrad for the initial angle and 27 for the number of turns to collapse. In obtaining Fig. 4 the injection is terminated at the 20<sup>th</sup> turn. The reason why the injection is terminated earlier than the turn number at which the bump collapse to zero is depicted in Fig. 5. This figure shows the number of accumulated particles as a function of the number of turns for old (plus marks) and new (cross marks) tunes and bump parameters mentioned above. The shaded bars in this figure indicate the number of desired accumulated macro particles (i.e. number of particles for 100% injection efficiency) injected per each turn. From this figure, one can see that before the improvement total number of turns required for injection seems to be around 15<sup>th</sup> because after this turn the number of accumulated particles does not increase further, meaning that the rate of the beam loss balances the rate of the injection.

The figure also shows that the number of turns required for injection after the improvement (i.e. with new tunes and bump parameters) is around 17. With the newly found tunes (1.82, 1.30) and the new bump parameters the injection efficiency was calculated to be 50.5%. This improvement is to be compared with the old efficiency, 33.5%. With these new parameters, the normalized horizontal phase space at the 1000<sup>th</sup> turn after the bump collapse is shown in Fig. 6. When this figure is compared with Fig. 3(a) and (b), one can see that the new phase portraits shows better behavior of beam stacking (i.e. beam is centered better).

For proton therapy, the required number of particles to a patient is  $1.5 \times 10^{10}$  per a spill. We assigned a total of  $6 \times 10^6$  real particles for a single macroparticle and 1000 macroparticles are used in the simulation study. With 20 turns for injection together with taking into consideration of losses during capture, acceleration and extraction, this number is sufficient even with the old tunes: for accumulated particles after the injection, we expect 10% additional loss during the capture, 20% additional loss during the acceleration and 10% additional loss during the extraction. Hence, we predict the number of survival real particles per a spill as  $6 \times 10^6 \text{ particles}/(\text{macro particle})/(\text{turn}) \times 1000 \text{ (macro particles)} \times 20(\text{turns}) \times \text{injection}$

efficiency( $\%$ ) $\times 90(\%) \times 80(\%) \times 90(\%)$ . The result is about  $2.1 \times 10^{10}$  for the old tune case and  $3.0 \times 10^{10}$  for the new tune case which are satisfying the required number of particles.

So far, space-charge effect is not included as mentioned before because inclusion of the space charge requires more computing time. To see briefly the effect of the space charge, 1000 macro particles are injected per each turn representing  $6 \times 10^9$  protons. Figure 7 shows the normalized horizontal phase space at the  $1000^{th}$  turn after the bump collapse with the old tunes (1.73, 1.47) and old bump parameters 4.8 mrad, 20-turn injection, and 20-turn linear pulse duration. It is found that the total injection efficiency decreases to 26.9%, approximately 20% reduction.

Figure 8 shows a similar plot with the new parameters. The injection efficiency in this case becomes 39%, again approximately 20% reduction from the case without space charge.

Figures 7 and 8 reveal structures of the phase space. This is believed to be higher-order resonances caused by tune shifts in the presence of space charge effect [9] but it requires more study.

## V. CONCLUSIONS

Increase in the efficiency for multi-turn injection of proton ions for a cancer therapy synchrotron has been treated in this paper. Transverse tunes are optimized by scanning tunes in the range  $1 < \nu_x, \nu_y < 2$ . Then kick angle and number of turns for injection and the pulse duration of the bump magnet were found which yielded most optimal injection efficiency. It is found that injection efficiency can be enhanced by 17 percentage-point when space-charge effect is not taken into account. In the presence of the space-charge effect, the efficiency is reduced by 20%. Effect of magnetic errors such as multipole components, closed orbit distortion is not treated in this paper and will be reported elsewhere.



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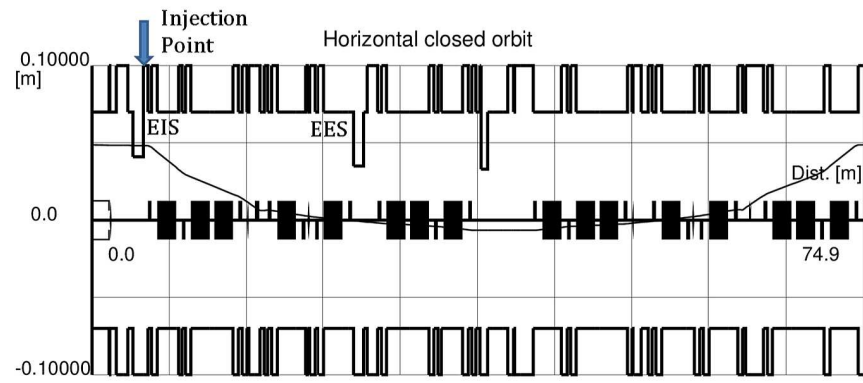


FIG. 1: [color on-line]The closed orbit path at the start of the injection

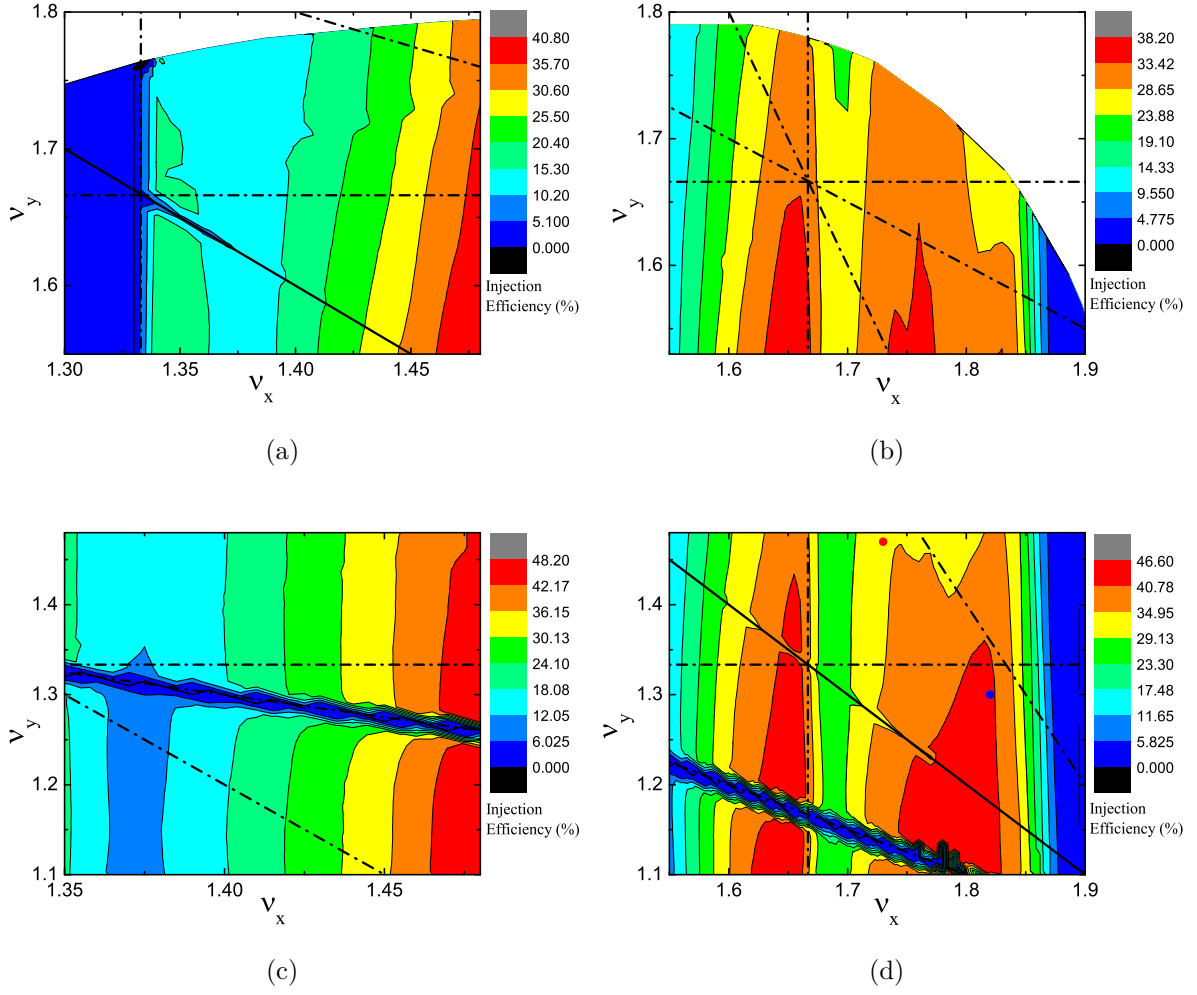
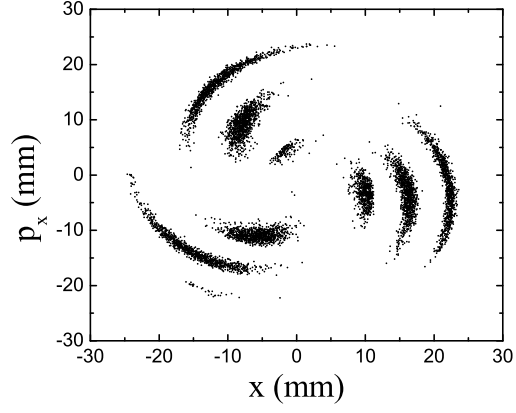
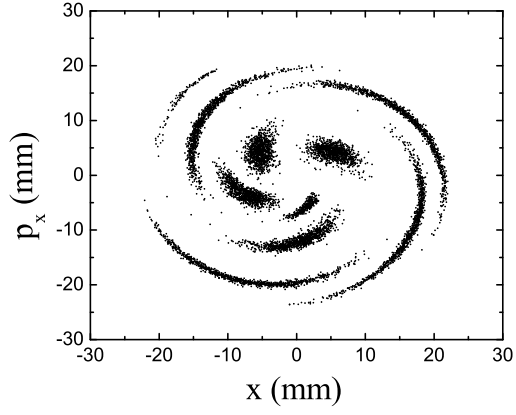


FIG. 2: [color on-line]Foot print for injection efficiencies for  $1 < \nu_x < 2$  and  $1 < \nu_y < 2$ . Solid line show the second-order resonances and dashed dot line indicate third-order resonances.



(a)



(b)

FIG. 3: Normalized horizontal phase spaces at 1000 turn after the bump collapse for (a) the initial tune (1.73, 1.47) and (b) the new tune (1.83, 1.30). In both cases, the maximum kick angle is 4.8 mrad and the bump pulse duration is 20 turns.

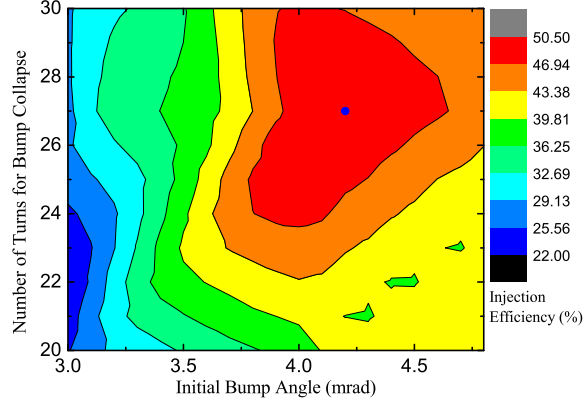


FIG. 4: [color on-line]Footprint for injection efficiencies as functions of initial kick angle of the bump magnet and the duration of the linear pulse. The dot indicates the selected value, 4.2 mrad and 27 turns

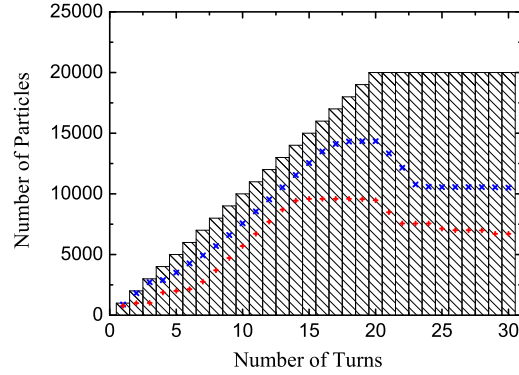


FIG. 5: [color on-line] Total number of accumulated particles as a function of the number of turns for old (plus marks) and new (cross marks) tunes and bump parameters. The shaded bars indicate the number of desired accumulated macro particles (i.e. number of particles for 100% injection efficiency) injected per each turn.

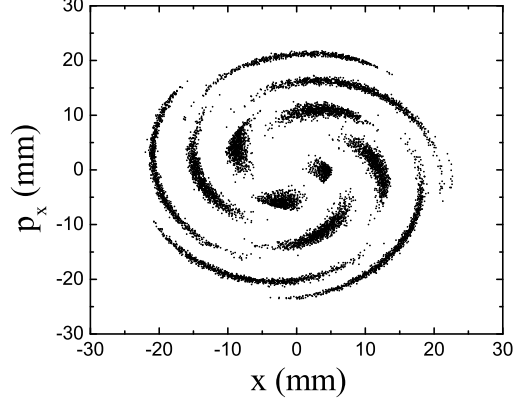


FIG. 6: Normalized horizontal phase space at 1000 turn after the bump collapse with the new tunes (1.82, 1.30) and new bump parameters 4.2 mrad and 27 turns. Space-charge effect is not included.

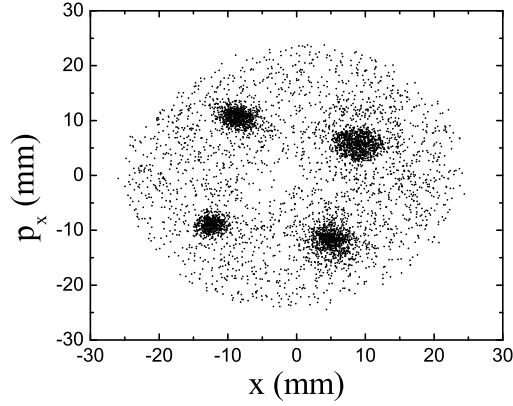


FIG. 7: Normalized horizontal phase space at 1000 turn after the bump collapse with the old tunes (1.73, 1.47) and old bump parameters 4.8 mrad, 20-turn injection, and 20-turn linear pulse duration. Space-charge effect is included. One macro particle represents  $6 \times 10^6$  protons and per each injection 1000 macro particles are injected.

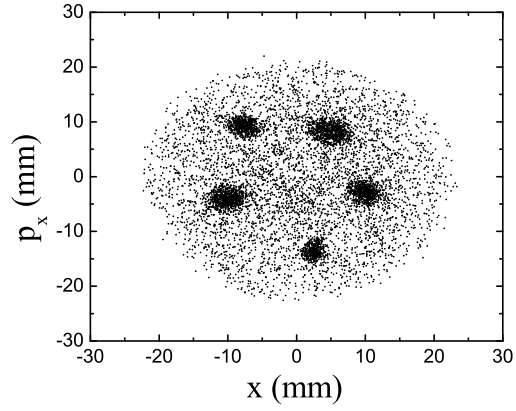


FIG. 8: Normalized horizontal phase space at 1000 turn after the bump collapse with the new tunes (1.82, 1.30) and new bump parameters 4.2 mrad and 27 turns. Space-charge effect is included. One macro particle represents  $6 \times 10^6$  protons and per each injection 1000 macro particles are injected.